

Final Progress Report: 09/15/01 - 09/14/05

Grant No. F49620-01-1-0543

ABCS Quantum Wells for Coherent THz Wave Generation

by J. Kono,¹ C. Z. Ning,² and M. Inoue³

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Personnel:

Graduate students:

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Research associates:

Dr. G. A. Khodaparast (Rice) and Dr. K. I. Kolokolov (NASA)

Senior researchers:

Dr. J. Li (NASA) and Prof. S. Sasa (Osaka)

Collaborators:

- Frank Tittel (Rice University): Spectroscopy with quantum cascade lasers
- Jerome Faist (University of Neuchatel): THz quantum cascade lasers
- Claire Gmachl (Princeton University): DFG in ABCS QWs using MIR quantum cascade lasers
- Alexey Belyanin (Texas A&M University): DFG calculations

Project Goal:

The goal of this project was to construct a compact and high power THz source based on antimonide-based semiconductors. Although we were unable to demonstrate such a device, our experimental and theoretical studies of intersubband resonances in InAs/AlSb quantum wells have significantly advanced understanding in this field. In particular, we expect our results to be applied in the rapidly-growing area of intersubband-based mid- and far-infrared emitters and detectors.

The achievements outlined in this report include:

- ❖ Observed intersubband absorption in wells as narrow as 2.1 nm at energies as high as 670 meV ($=1.85 \mu\text{m}$).
- ❖ Observed THz splitting in intersubband transitions (ISBTs) in coupled wells.
- ❖ Developed a microscopic theory of ISBT line broadening.
- ❖ Developed a theory of intersubband collective effects and plasmon coupling.

Project Motivation:

The goal of this project was to construct a compact and high power THz source based on antimonide-based compound semiconductors (ABCS). Our designs take advantage of the large

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conduction band offsets in ABCS to plan all-interband devices. This scheme could monolithically integrate a near-infrared (NIR) diode laser with the THz emitter.

The advantages of our optical approach for THz generation over electrical approaches are the absence of heavily doped layers for contacts and injectors which would increase absorption. Also, we can create carriers only in the wells contributing to THz generation, and we can utilize resonant nonlinearities to enhance the THz generation. This approach requires a sophisticated architecture of multi-level systems with tailored transition energies and matrix elements.

ABCS are ideal for the quantum engineering of energy levels wave functions. Their extremely deep conduction band wells lead to flexibility in subband level design. Figure 1(a) shows the band line-up of the ABCS. Figure 1(b) shows two proposed schemes for THz generation based on NIR interband pumping, both of which were demonstrated with CO₂ laser pumping in GaAs-based quantum well (QW) structures to produce coherent mid-infrared radiation.

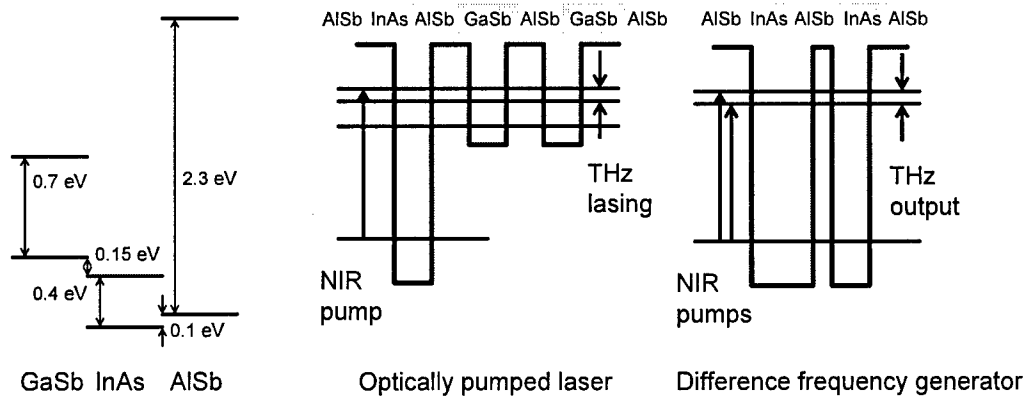


Figure 1: (a) Band gaps and offsets for ABCS heterostructures. (b) Two different schemes for intersubband THz generation with NIR pumping.

Sample Growth:

The samples were grown by molecular beam epitaxy at the Osaka Institute of Technology. Figure 2 shows the sample structure for GaAs and GaSb substrates. We have studied well widths from 1.8 to 10.5 nm, both with Si doping in the well and with unintentional doping. Hall measurements show that a high mobility 2DEG is present with the following parameters:

- ❖ RT mobility $< 1.7 \times 10^4$ cm²/Vs
- ❖ 77 K mobility $< 8.0 \times 10^4$ cm²/Vs
- ❖ RT density: $4.0 \times 10^{11} - 2.8 \times 10^{14}$ cm⁻² (unintentionally doped); $1.3 \times 10^{13} - 2.7 \times 10^{15}$ cm⁻² (Si doped)
- ❖ 77 K density: $3.0 \times 10^{10} - 4.5 \times 10^{14}$ cm⁻² (unintentionally doped); $8.7 \times 10^{12} - 2.7 \times 10^{15}$ cm⁻² (Si doped)

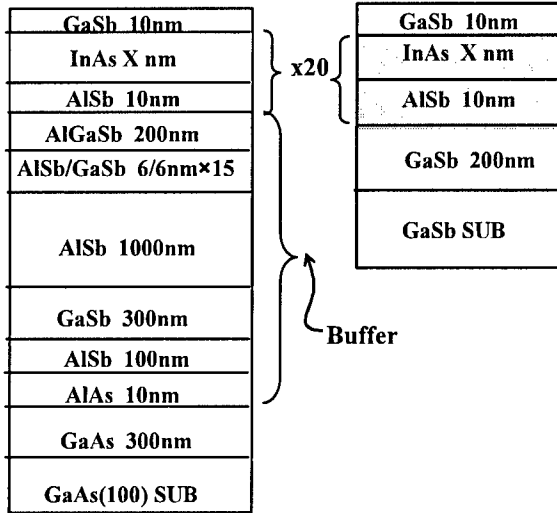


Figure 2: Two types of sample structure used in this work. The left structure has complicated buffer layers since the ABCS are grown on a lattice-mismatched GaAs substrate. The right structure is lattice matched but the GaSb substrate contains free carriers and is thus not ideal for THz applications.

We have studied the effects of a GaSb vs. a GaAs substrate, Si doping in the well, and InSb-like vs. AlAs-like interfaces. We have made high-resolution TEM measurements, which show high-quality, abrupt QW interfaces (Fig. 3).

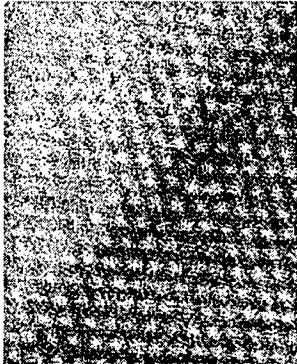


Figure 3: TEM image of InSb-like interface in InAs/ASb QW.

Intersubband Transitions:

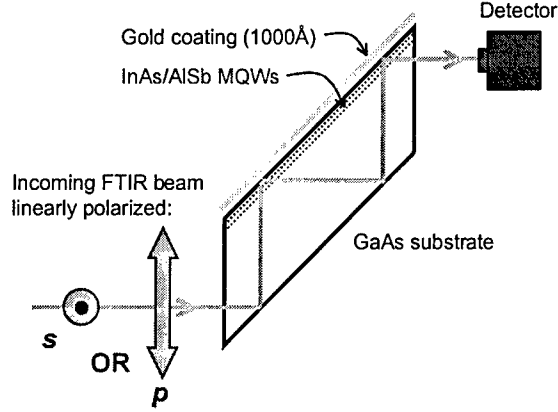


Figure 4: Intersubband absorption measurement geometry.

We have measured the intersubband absorption in all of the QWs. We detect the absorption via its polarization selection rule: E in the growth direction. We use the parallelogram measurement geometry, as shown in Figure 4. The sample is placed in a He flow cryostat.

Figure 5 shows the temperature dependence of the intersubband absorption we observed in 5 to 10 nm QWs. The absorption has a narrow linewidth and remains strong and sharp up to room temperature. These features make intersubband resonances a promising medium for room temperature THz generation.

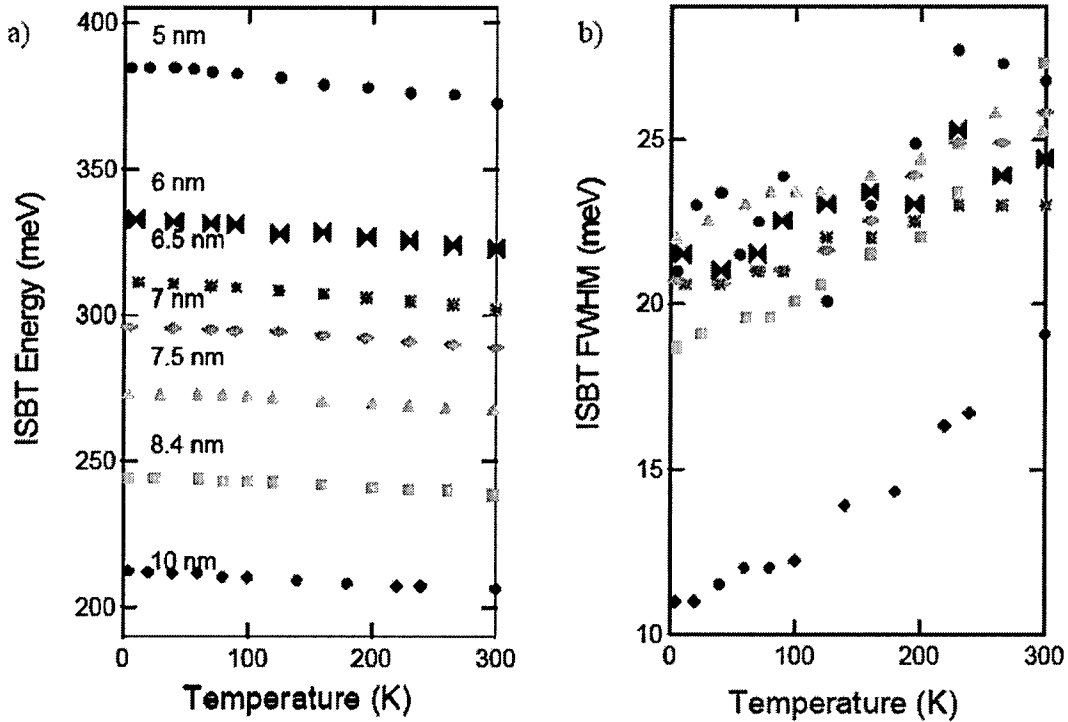


Figure 5: Temperature dependence of intersubband transition (a) peak energy and (b) full-width at half maximum.

We observed ISBTs in heavily doped 7 and 10 nm QWs grown on GaSb substrates. ABCS on GaSb substrates is suited to fill a spectral niche, $\sim 35\text{-}39\text{ meV}$ ($32\text{-}35\text{ }\mu\text{m}$), which is currently inaccessible to GaAs-based systems due to phonon absorption.

The most convenient pumping source for our THz generator would be a NIR diode, so we pursued high energy ISBTs. The key to observing high-energy resonances is heavily doping the QWs. We have observed intersubband absorption in wells as narrow as 2.1 nm with an electron density of $1 \times 10^{13}\text{ cm}^{-2}$, as shown in Figure 6. Despite the increased defects in the doped wells, their intersubband absorption is as strong and almost as narrow as the absorption of wider, undoped wells.

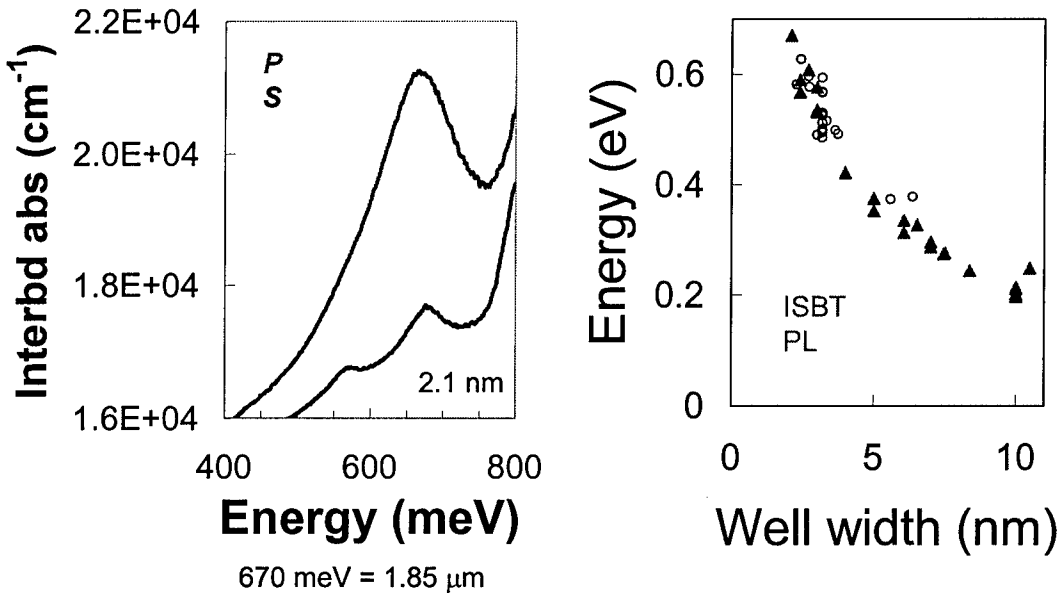


Figure 6: Left: Highest energy intersubband transition absorption spectrum. (*P* polarization: intersubband-active; *S* polarization: intersubband-inactive.) Right: Intersubband absorption and photoluminescence energies as a function of well width.

Designed and Grew Double Quantum Wells for Difference Frequency Generation:

We designed an asymmetric double quantum well structure for use as a difference frequency generator with mid-infrared pumps. The well widths and wavefunctions are shown in Figure 7(a). We chose to start with mid-infrared pumping energies rather than near-infrared because of the narrower intersubband resonances in wider wells.

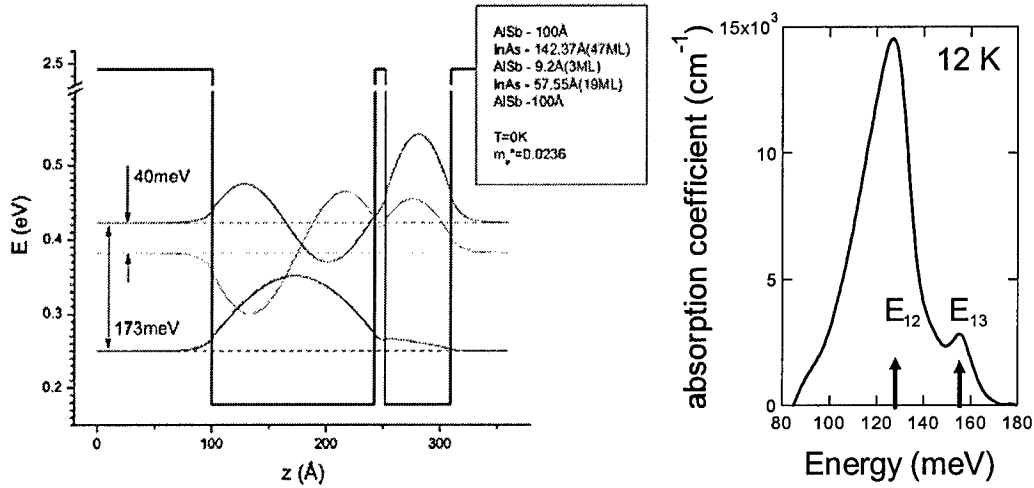


Figure 7: (a) Calculated wavefunctions of asymmetric coupled QWs for difference frequency generation. (b) Absorption coefficient of structure in (a).

We have observed THz splitting in a dozen asymmetric double quantum well structures designed for THz difference frequency mixing. For example, the double QW spectrum in Figure 7(b) shows sharp absorption peaks and a 30 meV splitting between MIR resonances. We observed THz splitting of the intersubband levels in double quantum well samples grown with and without Si doping.

Attempted Intersubband Difference Frequency Generation using MIR QCLs:

Our ultimate goal is to perform difference frequency mixing of NIR diodes. However, we are still working on increasing the single well E_{12} to 1.55 μm . Therefore, we chose to test our system by mixing MIR lasers with a THz energy separation. We borrowed three MIR QCLs from Claire Gmachl (Princeton University). They have wavelengths of 10.4, 8.4, and 7.4 μm (119, 148, and 165 meV) and high peak powers of 100, 100, and 800 mW, respectively. Several combinations of lasers were resonant with various samples; the sample shown in Fig. 8 had the highest predicted THz power. We attempted difference frequency generation at difference energies of 46 meV = 27 μm and 17 meV = 73 μm .

In collaboration with Alexey Belyanin, we developed a model for the DF power in our non-phase-matched system. According to this model, the maximum allowable path length through the nonlinear medium is about 0.5 mm. So, we chose an edge-coupling geometry to maximize the DF power. We compared the nonlinear susceptibilities, $\chi^{(2)}$, of our double quantum well structures to choose the combination of electron density, ISB peak width, and energy which best matched our MIR QCLs. We also considered several phase-matching schemes: interaction with the phonon resonance or intersubband absorption of an additional layer, phase mismatch tuning by waveguide plateau width adjustment, and path length adjustment in a multi-bounce scheme. However, none of these schemes offered a significant benefit in this first-order attempt.

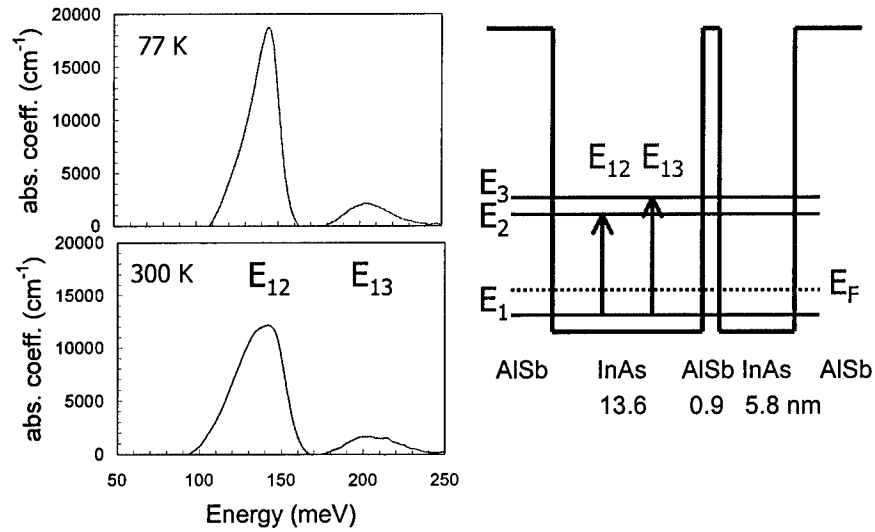


Figure 8: Left: Intersubband absorption spectra of the sample structure shown at right. This sample has the largest calculated DFG power for our MIR QCLs. Note that the intersubband absorption remains strong and sharp even at room temperature.

Our experimental setup is shown schematically in Fig. 9. We achieved a peak intensity at the sample of 0.9 kW/cm^2 for the $10.4 \text{ }\mu\text{m}$ laser and 1.4 kW/cm^2 for the $7.4 \text{ }\mu\text{m}$ laser, with 80 ns pulses at 2% duty cycle. Although we predicted a DF peak power of about 300 pW for the sample shown in Fig. 2, we were unable to observe any nonlinear generation.

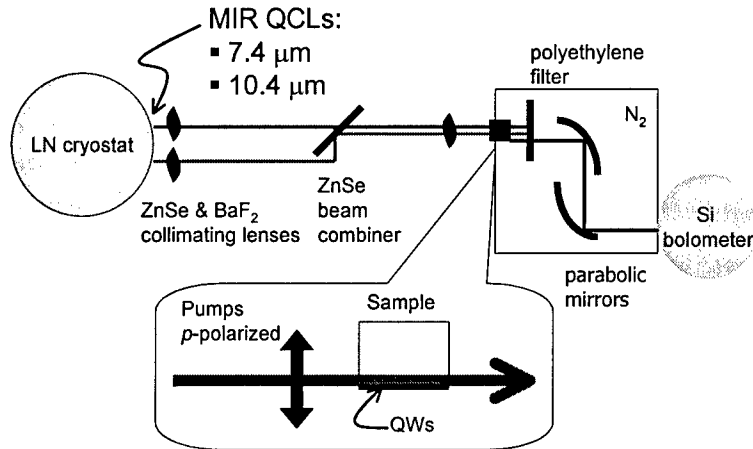


Figure 9: Experimental setup for difference frequency generation.

We also attempted another THz generation scheme based on pumping with a powerful, ultrafast MIR laser. Due to the broad frequency spread of the ultrafast laser, a

single beam is predicted to excite a coherent oscillation between the E_2 and E_3 levels, resulting in tens of pW of THz emission. Unfortunately, we were unable to observe difference frequency generation in this configuration.

Detailed Theory of ISBT Broadening Mechanisms:

We have developed a detailed theory of the intersubband absorption spectrum.

	Static	Dynamic
Direct	Screening, Band bending	Depolarization shift
Exchange	Self-energy correction	Vertex (excitonic) correction

Table 1: Coulomb interactions included in intersubband absorption model.

We begin with a realistic 8-band $k \cdot p$ calculation of the nonparabolic subbands. Then, we calculate the absorption spectrum using the semiconductor Bloch equations (SBEs). The SBEs describe the interaction of a semiconductor with light through the dipole interaction. We use this formalism to incorporate coherent and incoherent light-

semiconductor interactions by taking into account band dispersions, Coulomb interactions, and decoherence and relaxation

processes including phonon scattering and interface roughness scattering. This is one of the first cases where they are applied to intersubband dynamics.

Many-body interactions play a critical role in intersubband absorption, and we have included their effects via the SBEs. Table 1 shows the four types of Coulomb interactions which have been incorporated in our theory. Figure 10 shows the effects of the many-body interactions one at a time. Figure 10(a) is the single-particle spectrum, which is broad due to nonparabolicity. Adding the self energy shifts the resonance to higher energy and broadens it slightly, as does the depolarization shift. The vertex correction causes a strong redshift and a dramatic narrowing of the resonance. The vertex correction turns out to be the dominant effect in this regime of carrier density and well width.

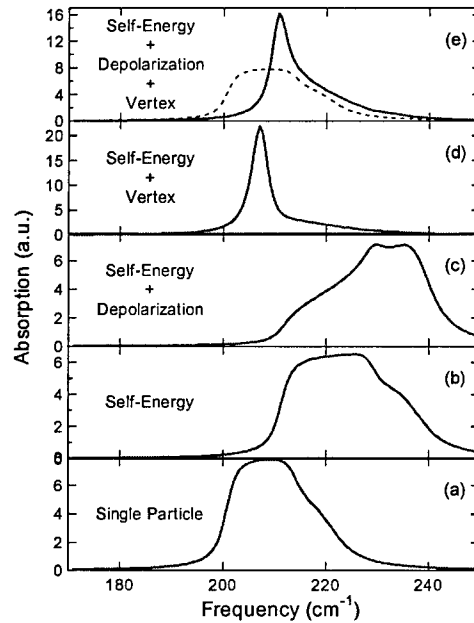


Figure 10: Effects of the many body interactions on the intersubband absorption spectrum of a 10 nm QW.

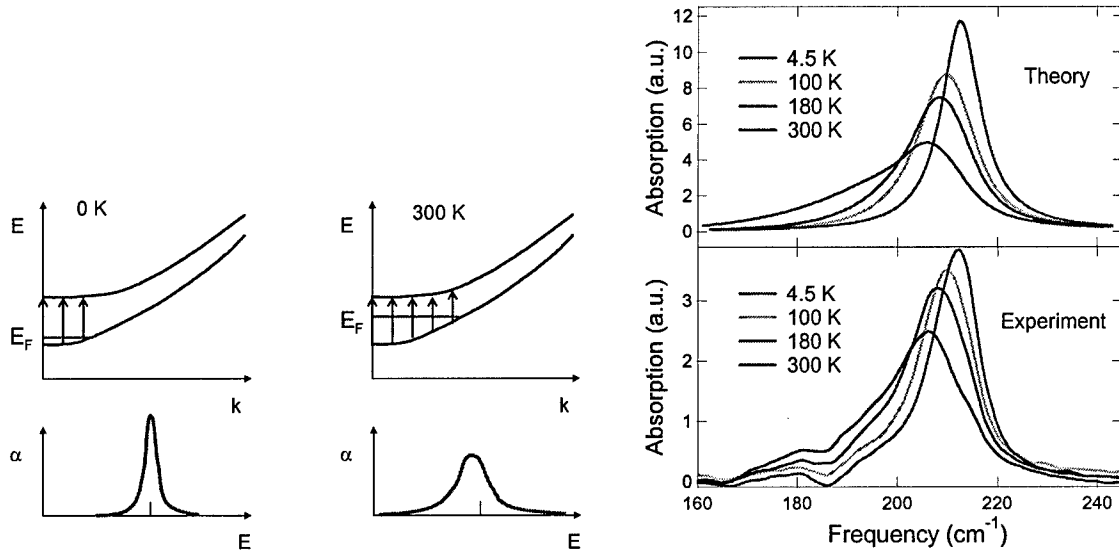


Figure 11: Nonparabolic dispersion relation and absorption coefficient at (a) 0 K and (b) 300 K. The arrows indicate the single-particle ISBA energies. (c) Calculated and experimental intersubband absorption of 10 nm QW as a function of temperature.

The temperature dependence of the ISBT is simply incorporated through the carrier density, band filling, and nonparabolicity. At low temperatures, the carrier density is low and the carriers are all at the lowest possible energies [Fig. 11(a)]. This gives the minimum nonparabolicity broadening and a sharp absorption line. At room temperature, the carrier density is about three times higher and the carriers are thermally excited to higher energies in the subband [Fig. 11(b)]. This redistribution strongly increases the nonparabolicity broadening, shifting the resonance to lower energy and broadening it. Figure 11(c) shows the excellent agreement achieved between experiment and theory for the temperature dependence of the intersubband lineshape for a 10 nm QW.

The NASA group published several further analyses of collective effects in intersubband resonances. One is an extension of their previous description based on the Intersubband Semiconductor Bloch Equations which treats dephasing in a more detailed way. They find changes in the intersubband absorption lineshape due to the interaction of the Fermi-edge singularity and the intersubband plasmon. Another analysis predicts the appearance of transparency induced by out-of-phase intersubband plasmon coupling. This effect can be observed by tailoring the electron population. A third study shows that by correctly including electron-electron and electron-phonon interactions, their theory predicts a smaller linewidth for GaAs-based ISBTs, in agreement with experiment. These works explore fundamental physics and have application to the many intersubband light generation and detection mechanisms in the mid and far infrared.

Other Accomplishments:

Understood Carrier Distribution in QWs:

We have used Shubnikov-deHaas (SdH) measurements in conjunction with Hall measurements to elucidate the carrier distribution in our nominally undoped 20-period QW samples. Whereas the Hall effect measures all of the carriers in the entire sample, the SdH effect is sensitive only to the high-mobility 2DEGs in the QWs. We find two regimes of carrier distribution, illustrated in Fig. 12. Early in the MBE growth run, the SdH density equals twenty times the Hall density. This indicates that the carriers are distributed uniformly throughout the QWs. After about 30 growths, the SdH density is much greater than 20 times the Hall density, indicating that the carriers are concentrated in only a few QWs. We attribute this behavior to a constant Fermi level pinning at the sample surface coupled with a decreasing density of unintentional donors in the AlSb barriers. This understanding was important for achieving higher energy ISBTs.

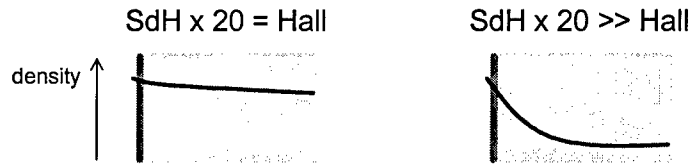


Figure 12: The inferred density profile through the multiple QW region (left) early and (right) late in the MBE growth run.

First Spectroscopy with THz QCL:

We have obtained pulsed and CW THz quantum cascade lasers (QCLs) from Jerome Faist's group (U. Neuchatel), in collaboration with Frank Tittel (Rice U.). The lasers operate at 64 μm (4.7 THz), 86 μm (3.5 THz), and 127 μm (2.3 THz), with a typical threshold current of 210 A/cm² and peak power $< \sim 4$ mW.

We have made the first spectroscopy application of a THz QCL, as shown in Figure 13. We measured cyclotron resonance in 9 nm InAs QWs to find $m^*(T)$. We expected E_g to decrease with increasing temperature, causing m^* to decrease. Instead, we observed that m^* increases with increasing temperature. These results will improve our modeling of the temperature dependence of the ISBT.

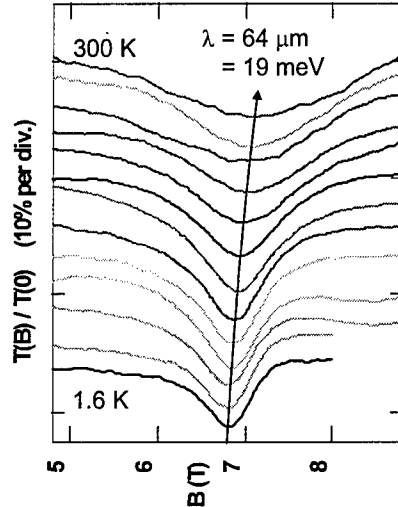


Figure 13: Cyclotron resonance in 9 nm InAs QWs showing increase in m^* with increasing temperature.

Papers Generated by This Work:

- J. Li, K. I. Kolokolov, C. Z. Ning, D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, S. Sasa, and M. Inoue, "Microscopic Modeling of Intersubband Resonances in InAs/AlSb Quantum Wells," *Physica E* **20**, 268 (2004).
- D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Temperature Dependence of Intersubband Transitions in InAs/AlSb Quantum Wells," *Applied Physics Letters* **83**, 3936 (2003).
- D. C. Larrabee, G. A. Khodaparast, F. K. Tittel, J. Kono, M. Rochat, L. Ajili, J. Faist, H. Beere, E. Linfield, Y. Nakajima, M. Nakai, S. Sasa, M. Inoue, S. J. Chung, and M. B. Santos, "Application of Terahertz Quantum Cascade Lasers to Semiconductor Cyclotron Resonance," *Optics Letters* **29**, 122 (2004).
- J. Li and C. Z. Ning, "Interplay of Collective Excitations in Quantum-Well Intersubband Resonances," *Phys. Rev. Lett.* **91**, 097401 (2003).
- K. I. Kolokolov, J. Li, and C. Z. Ning, "k-p Hamiltonian without spurious-state solutions," *Phys. Rev. B* **68**, 161308(R) (2003).
- J. Li and C. Z. Ning, "Many-body effects on intersubband resonances in narrow InAs/AlSb quantum wells," *Physica E* **20**, 264 (2004).
- J. Li and C. Z. Ning, "Collective excitations in InAs quantum well intersubband transitions," *Physica E* **22**, 628 (2004).

- J. Li and C. Z. Ning, "Induced Transparency by Intersubband Plasmon Coupling in a Quantum Well," *Phys. Rev. Lett.* **93**, 087402 (2004).
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- J. Li, C. Z. Ning, "Effects of electron-electron and electron-phonon scatterings on the linewidths of intersubband transitions in a quantum well," *Phys. Rev. B* **70**, 125309 (2004).
- D. C. Larrabee, J. Tang, M. Liang, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, and C. Z. Ning, "Intersubband transitions in narrow InAs/AlSb quantum wells," in: *Proceedings of the 26th International Conference on the Physics of Semiconductors*, edited by A. R. Long and J. H. Davies (Institute of Physics Publishing, Bristol, 2003), P129.
- D. C. Larrabee, J. Tang, M. Liang, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, O. Suekane, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, C. Z. Ning, "Intersubband Transitions in Narrow InAs/AlSb Quantum Wells" in: *Proceedings of the 1st IEEE Lester Eastman Conference on High Performance Devices*, edited by L. Lunardi, J. C. Zolper, R. E. Leoni, J. Kolodzey, and E. Kohn (IEEE, Piscataway, 2002, ISBN: 0-7803-7478-9), pp. 324-333.
- J. Tang, D. C. Larrabee, B. E. Brinson, G. A. Khodaparast, J. Kono, M. Karasaki, K. Ueda, S. Sasa, M. Inoue, K. I. Kolokolov, J. Li, C. Z. Ning, "Evaluation of Interfaces in Narrow InAs/AlSb Quantum Wells" in: *Proceedings of the 1st IEEE Lester Eastman Conference on High Performance Devices*, edited by L. Lunardi, J. C. Zolper, R. E. Leoni, J. Kolodzey, and E. Kohn (IEEE, Piscataway, 2002, ISBN: 0-7803-7478-9), pp. 223-227.
- J. Li, K. I. Kolokolov, C. Z. Ning, D. C. Larrabee, G. A. Khodaparast, J. Kono, K. Ueda, Y. Nakajima, S. Sasa, and M. Inoue, "Intersubband Transitions in InAs/AlSb Quantum Wells" (**invited paper**), in: *MRS Proceedings Volume 744, Progress in Semiconductors II – Electronics and Optoelectronic Applications*, edited by B. D. Weaver, M. O. Manasreh, C. C. Jagadish, and S. Zollner (Materials Research Society, 2003), pp. M9.2.1-M9.2.12.

Veon Wendy M Civ AFRL/AFOSR

From: Sarah Phillips [sPhillips@rice.edu]
Sent: Thursday, December 15, 2005 12:46 PM
To: Veon Wendy M Civ AFRL/AFOSR
Subject: RE: Rice University: AFOSR Final Report Submission

Dear Wendy,

I used the wrong name in my previous email to you. I do apologize for this error. My only excuse is that I'm currently taking a lot of cold medicine and had just received an email from someone who was named Nancy. I normally do not make errors of this nature. I hope I have not offended you.

Again, I am sorry and thank you for your patience.

Sarah

~~~~~  
Sarah Phillips  
International Programs Administrator  
Electrical and Computer Engineering  
Abercrombie Lab A-101

Rice University  
6100 Main St. - MS 366, PO Box 1892  
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-----Original Message-----

From: Sarah Phillips [mailto:sPhillips@rice.edu]  
Sent: Thursday, December 15, 2005 11:28 AM  
To: Veon Wendy M Civ AFRL/AFOSR; AFRL/AFOSR PK Contracting  
Cc: Jun Kono; Henn Landberg; Diane Larrabee; gernot.pomrenke@afosr.af.mil  
Subject: RE: Rice University: AFOSR Final Report Submission  
Importance: High

Dear Nancy,

I apologize for the error in funding number that I submitted yesterday. In looking further in the files for this grant I was able to locate the correct funding number along with the contact information for Gernot S. Pomrenke who I have also copied to this message. Attached please find the updated final report for the following:

Final Progress Report: 09/15/01 - 09/14/05 Grant No. F49620-01-1-0543 Antimonide-Based Semiconductor Quantum Wells for Coherent Terahertz Wave Generation

I will also resend two hard copies of this report to your office for you and Mr. Pomrenke. Please let me know if you have any further questions regarding this submission.

Kind regards,

Sarah

~~~~~  
Sarah Phillips
International Programs Administrator
Electrical and Computer Engineering

Abercrombie Lab A-101

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Fax: 713/348-5686
Email: sphillips@rice.edu
<http://www.innovateconference.org>

-----Original Message-----

From: Veon Wendy M Civ AFRL/AFOSR [mailto:wendy.veon@afosr.af.mil]
Sent: Thursday, December 15, 2005 6:29 AM
To: Sarah Phillips; AFRL/AFOSR PK Contracting
Cc: Jun Kono; Henn Landberg; Diane Larrabee
Subject: RE: Rice University: AFOSR Final Report Submission

Hello Ms. Phillips,

Would you please verify the award number shown in your email and on the documents attached to the email? The award number F49620-01-1-0406 does not show it belongs to Rice University or Professor Kono. Since I was unable to make a match the report was not cleared from the delinquency listing. Your help is appreciated.

Thank you,
Wendy

Wendy M. Veon
Administrative Contracting Officer

AFOSR/PKC
875 North Randolph Street
Suite 325, Room 3112
Arlington, VA 22203-1768

Phone: 703-696-7286
FAX: 703-696-9733

e-mail: wendy.veon@afosr.af.mil
pkcontracting@afosr.af.mil

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-----Original Message-----

From: Sarah Phillips [mailto:sphillips@rice.edu]
Sent: Wednesday, December 14, 2005 5:36 PM
To: AFRL/AFOSR PK Contracting
Cc: Jun Kono; Henn Landberg; Diane Larrabee
Subject: FW: Rice University: AFOSR Final Report Submission
Importance: High

Dear Ms. Veon,

Attached please find the following report submitting on the behalf of Junichiro Kono.

Final Progress Report: 09/15/01 - 09/14/05 Grant No. F49620-01-1-0406 ABCS Quantum Wells for Coherent THz Wave Generation

I wanted to send off this report to you today to ensure it has been submitted to someone at AFOSR by the due date of 12/14/2005. Please let me know if this needs to be resent to another individual in your office. I have also sent a hard copy of this report via FedEx with tracking number 790254943342.

Please contact me with any further questions or if this needs to be redirected to another individual.

Kind regards,

Sarah Phillips

~~~~~  
Sarah Phillips  
International Programs Administrator  
Electrical and Computer Engineering  
Abercrombie Lab A-101

Rice University  
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Houston, TX 77251-1892  
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-----Original Message-----

From: Sarah Phillips [mailto:sphillips@rice.edu]  
Sent: Wednesday, December 14, 2005 10:38 AM  
To: pkcontracting@afosr.af.mil  
Cc: Jun Kono  
Subject: Rice University: AFOSR Final Report Submission

Dear Ms. Veon,

I was provided your contact information by the Office of Sponsored Research here at Rice University. I am the new International Programs Administrator who will be working with Junichiro Kono and his research group on a number of programs as well as administrative oversight of his grants. Jun is currently out of the country and has asked me to assist him in the submission of the following final report:

Final Progress Report: 09/15/01 - 09/14/05 Grant No. F49620-01-1-0406 ABCS Quantum Wells for Coherent THz Wave Generation

As this is the first time I have submitted a final report to the AFOSR I had a couple of questions that I was hoping you could assist me with.

1. The Final Performance Report instructions indicate the report should be mailed to the Program Manager. Would this be to you?
2. If yes, I can mail the report off today and provide you with the FedEx tracking number for the shipment. If you would prefer, I can also submit this report via a PDF attachment to an email.
3. The Final Performance Report instructions also indicate that the pages should be prepared for acquisition and distribution by DTIC. I've reviewed the DTIC website and believe we will need to apply for a DTIC submission number. Is this something that can be done after the report has been submitted or would you prefer we wait to submit the report until we can list the DTIC submission number on the cover sheet?
4. Can you give any further guidance regarding the DTIC acquisition and distribution process?
5. Finally, on the Report Documentation Page I was unsure what to list in item 14 under Subject Terms? I am not sure if this field applies to our grant or not.

Please let me know if I can provide you with any further information that would assist you

- in addressing these questions. Also, please forward these questions to the correct Program Manager if I have been provided your contact information in error. We appreciate any assistance you can provide.

Thank you,

Sarah Phillips

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13. ABSTRACT (Maximum 200 Words) The goal of this project was to construct a compact terahertz (THz) source based on antimonide-based compound semiconductor (ABCS) quantum wells. The large conduction band offsets achievable with these materials make it possible to design and fabricate unique structures in which both near-infrared pumping and THz emission energies resonate with intersubband transitions. This all-intraband-transition scheme provides the ability to tune the THz emission wavelength entirely independently of the band gaps. Single and double quantum well structures were grown by molecular beam epitaxy and characterized spectroscopically to determine their absorption and gain spectra. The results were compared with detailed theoretical modeling and simulations. THz generation was attempted by difference frequency mixing in resonant double quantum wells. No THz emission was detected. However, this project has made unique contributions to the experimental and theoretical understanding of intersubband resonances over a wide range of temperatures, carrier densities, and well widths. This new understanding will have a significant impact on the many intersubband-based mid- and far-infrared emitters and detectors, and in particular on short-wavelength ABCS quantum cascade lasers.				
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